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Effect of breaking waves on scour processes around circular offshore wind turbine foundations

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Introduction

Scour and scour protection are major issues to consider when constructing offshore wind farms. The majority of wind farms to be built are situated in environments characterized by strong influence of tides, wind-induced currents and waves breaking.

If the turbines are placed without protection on an erodible seabed, a scour hole will develop. The engineer can either include the scour in his design, or he can place a scour protection on the seabed. Which of the two solutions is the most attractive depends on the cost of providing scour protection compared with the extra cost of making the pile stronger/longer, extra cable dredging etc. The optimal solution will depend to a large extent on the maximal scour depth an unprotected foundation will experience during its lifetime.

For many years, engineers designing bridges have been used to taking into account scour around structures exposed to steady currents. Hoffmanns and Verheijs (1997) is an example of a book giving a good overview of this topic. The typical fully-developed scour depth in a uniform current is 1 to 1.5 times the pile diameter, resulting in a typical maximum scour depth in the range of 5-8 m for a typical pile with a diameter equal to 5 m.

However, wave scour has never received much attention, perhaps because scour depths in oscillatory flows are normally much smaller than scour depths in steady currents. Nevertheless, with the development of offshore wind farms, there has been a growing focus on wave scour. An excellent book to give an overview of wave scour, and scour in combinations of waves and currents, is the book by Sumer and Fredsøe (2002).

In pure waves, the scour depth increases with the KC number (which can be expressed as the ratio between the orbital motions near the bed compared with the pile diameter). Sumer and Fredsøe suggest the maximum scour depth S to be calculated from $S = 0.1D \cdot \sqrt{KC}$ in case of horizontal piles. For small KC numbers, it seems appropriate to use this equation for a vertical pile. For a typical pile foundation with a diameter equal to 5 m, in typical wave conditions, the maximum scour depth will normally be less than 2 m.

In a combination of waves and currents, the scour depth becomes smaller than for current alone. This means that if a pile is located in an area with strong tidal currents, the scour becomes smaller during storm periods.

Bijker and Bruyn (1988) describe the erosion around a pile due to currents and breaking waves and give some indications for scour depths. However, the effect of breaking waves has not yet been studied in detail.

Today's practice has not yet been defined, but some engineers include possible wave breaking in their design by increasing scour depth for current alone. That is, the design scour depth is considered to be more than 1.5 times the pile diameter.

The present study includes some studies of scour processes in physical models as well as in a numerical model, under the influence of breaking and broken waves. Wave breaking may be caused by the seabed or by the presence of the windmill foundation itself.

Test Set-up

Tests in a length scale 1:30 were performed in a wave flume at the Hydraulics and Coastal Laboratory, Aalborg University. The flume is 18.7 m long and 1.2 m wide, see figure 1. A two-way pump able to circulate 650 l water per second is mounted beneath the flume.

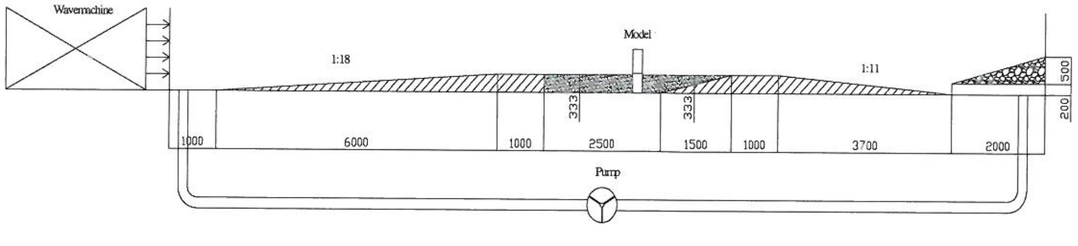


Figure 1. The wave flume. All measurements in millimetres.

The sloping bed was constructed in order to increase wave breaking. It was possible to ensure a reasonable velocity profile. The bed was constructed of concrete with a 4 m long sand box filled with fine sand, $d_{50} = 0.17mm$. In table 5 later in the paper, the Shields Parameter is calculated for all test cases, showing that a live bed condition was achieved in all tests. Before filling the sand box, a monopile was fixed to the concrete. Sand was spread out in a thin layer across the slopes to simulate the natural bed sediment transport in the sandbox.

Scour holes were measured in a 1.5 cm by 1.5 cm grid using a laser profiler. The measured grid was 1.5 m long and 0.93 m wide. Waves and currents were measured beside the model. Waves were separated into incident and reflected waves.
In Larsen et. al. (2005) a more detailed description of the test set-up can be found.

Test programme

The present paper focuses on the effects of breaking waves on scour. However, the tests listed in the following pages are only part of a more comprehensive test programme on scour around offshore wind turbines in areas with strong currents. In Larsen et al. (2005) more test results can be found.

Test no	**Comments**	**Diameter of monopile D [m]**	**Significant wave height H_s [m]**	**Spectral peak period T_p [s]**	**Water depth seaward d_0 [m]**	**Water depth at pile h_t [-]**	**Current induced velocity U_c [m/s]**
1.1	*Breaking*	0.10	0.12	1.28	0.62	0.29	0.00
1.2	*waves, with*	0.10	0.12	2.01	0.62	0.29	0.00
1.3	*and without*	0.10	0.08	1.28	0.50	0.17	0.00
1.4	*unidirectio-*	0.10	0.08	2.01	0.50	0.17	0.00
1.5	*nal current*	0.10	0.12	1.28	0.62	0.29	0.30
1.6		0.10	0.12	2.01	0.62	0.29	0.30

Table 1. Test programme for the scour tests. Irregular waves.

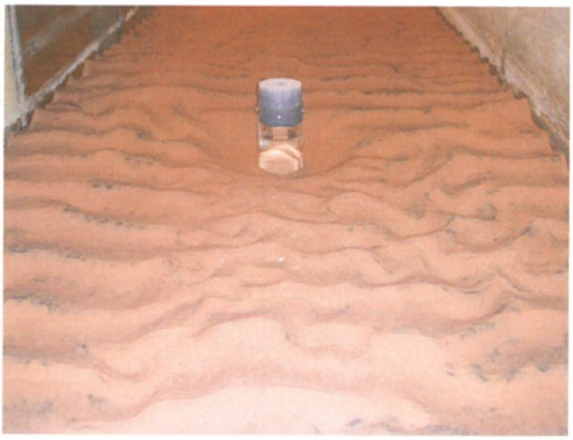
Test no	**Comments**	**Diameter of monopile D [m]**	**Wave height H [m]**	**Period T [s]**	**Water depth seaward d_0 [m]**	**Water depth at pile h_t [-]**	**Current induced velocity U_c [m/s]**
3.1	*Regular*	0.20	0.10	1.28	0.50	0.17	0.00
3.2	*Waves*	0.20	0.10	2.01	0.50	0.17	0.00
3.3		0.20	0.10	2.50	0.50	0.17	0.00

Table 2. Test programme for the scour tests. Regular waves.

The main purpose of the irregular tests was to study the effects of wave breaking by making comparisons with tests from literature, performed with non-breaking waves.

The main purpose of the tests with regular waves was to compare with the calculations in the numerical model.

Results from physical tests



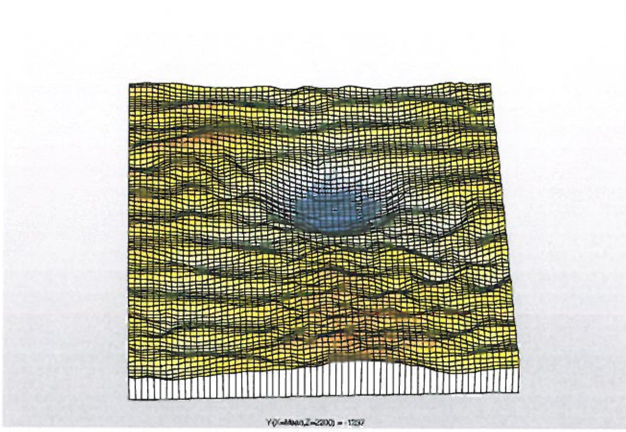


Figure 2. Photo/measurement showing scour hole after 1500 waves. Test 1.5. Please note that in the photo, the upper part of the pile has been temporarily removed in order to make the profiling.

Test no	Diameter of monopile D [m]	Significant wave height H_s [m]	Spectral peak period T_p [s]	Water depth at pile h_t [-]	Current induced velocity U_c [m/s]	Scour depth S [m]	Relative scour depth S/D [-]
1.1	0.10	0.11	1.31	0.29	0.00	0.012	0.120
1.2	0.10	0.12	1.97	0.29	0.00	0.020	0.200
1.3	0.10	0.07	1.28	0.17	0.00	0.011	0.110
1.4	0.10	0.08	1.97	0.17	0.00	0.014	0.140
1.5	0.10	0.11	1.31	0.29	0.30	0.078	0.780
1.6	0.10	0.12	1.97	0.29	0.30	0.078	0.780

Table 3. Results from physical tests. Irregular waves.

Test no	Diameter of monopile D [m]	Wave height H [m]	Period T [s]	Water depth at pile h_t [-]	Current induced velocity U_c [m/s]	Scour depth S [m]	Relative scour depth S/D [-]
3.1	0.20	0.10	1.28	0.17	0.00	0.019	0.095
3.2	0.20	0.11	2.01	0.17	0.00	0.032	0.160
3.3	0.20	0.09	2.50	0.17	0.00	0.026	0.260

Table 4. Results from physical tests. Regular waves.

Using the methodology given by Sumer and Fredsøe (2002), it is possible to compare our results with the results for the non-breaking waves listed by Sumer and Fredsøe (2002).

Figure 3 shows the measured maximum scour depth S (S/D in dimensionless form) as a function of the combined wave-current velocity Ucw. $U_{cw} = Uc/(Uc + Um)$. See Sumer and Fredsøe (2002) for a full definition of U_{cw}.

Test no	KC	U_{cw}	θ
1.1	2.6	0	0.058
1.2	5.7	0	0.108
1.3	3.4	0	0.103
1.4	7.1	0	0.164
1.5	2.6	0.61	0.186
1.6	5.7	0.51	0.241

Table 5. Calculated KC , U_{cw} and 6 values for the test cases.

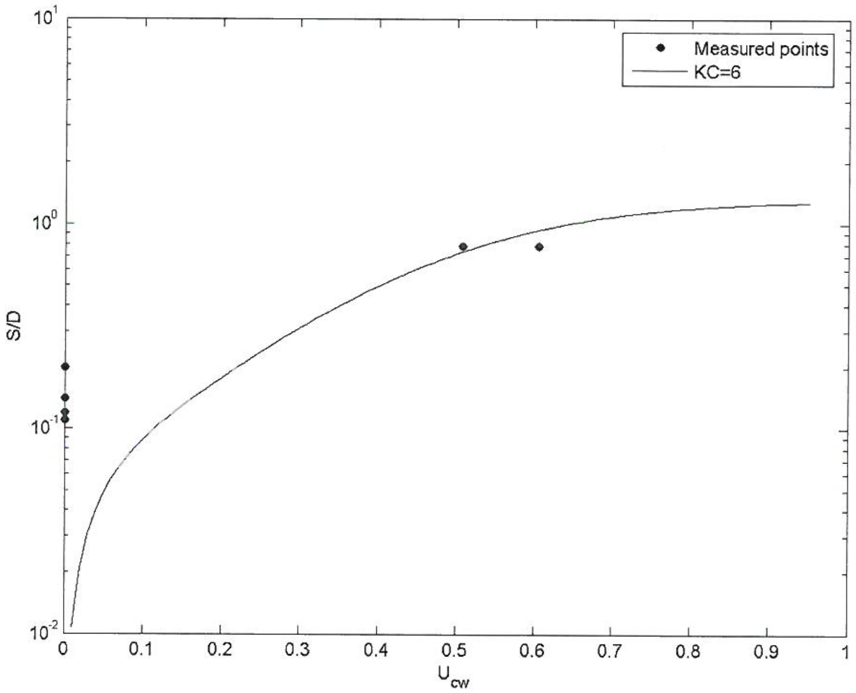


Figure 3. Comparison of predicted scour for non-breaking waves calculated according to Sumer and Fredsøe, with KC=6 (Solid line), and measured scour for breaking waves (Dots).

Numerical investigations

The numerical investigations are based on the three-dimensional Navier-Stokes solver NS3. The method has been described in Mayer et al. (1998), Emarat et al. (2000), Nielsen and Mayer (2004), and Christensen et al. (2005).

The spatial discretisation is based on the finite-volume approach on a multi-block grid. The time integration of the Navier-Stokes equations is performed by application of the fractional step method. Figure 4 shows an example of the multi-block grid used for the study. The grid consists of 12 blocks.

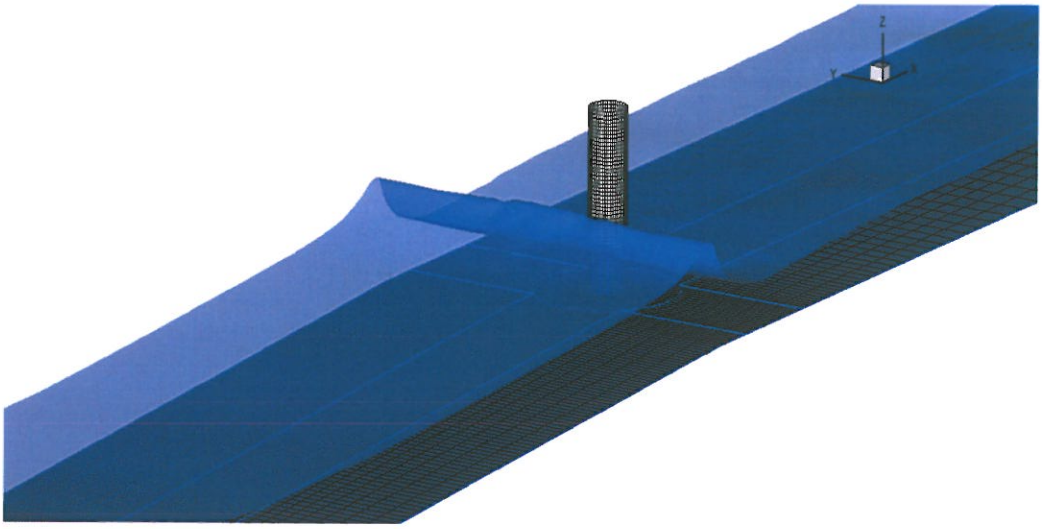


Figure 4. The multi-block structure of the computational domain shown at the bed (thick blue lines). The grid consists of twelve 3D blocks of structured data cells.

The free surface is resolved using a Volume-of-Fluid (VOF) description, with an improved scheme for the advection of the conservative quantity, F, cf. Ubbink (1997).

The scour development is mainly governed by the flow close to the seabed and the seabed properties. In order to study the influence from breaking waves, the flow is examined numerically for the same near-bed properties with and without the influence of breaking waves. The numerical model has been set up for the same near-bed flow properties as the physical scour experiments.

Numerical parameters

NS3 has been set up for 10 simulations described by the following parameters, see figure 5.

D_cyl:	Depth at the cylinder
D_in:	Depth at inlet boundary
H_cyl:	Shoaled wave height at the cylinder
H_in_bound:	Wave height at inlet boundary
T:	Wave period
L_cyl:	Wave length at cylinder
Ks:	Shoaling coefficient
Dia:	Diameter of the cylinder
Dist:	Distance from center of the cylinder to the beginning of the slope

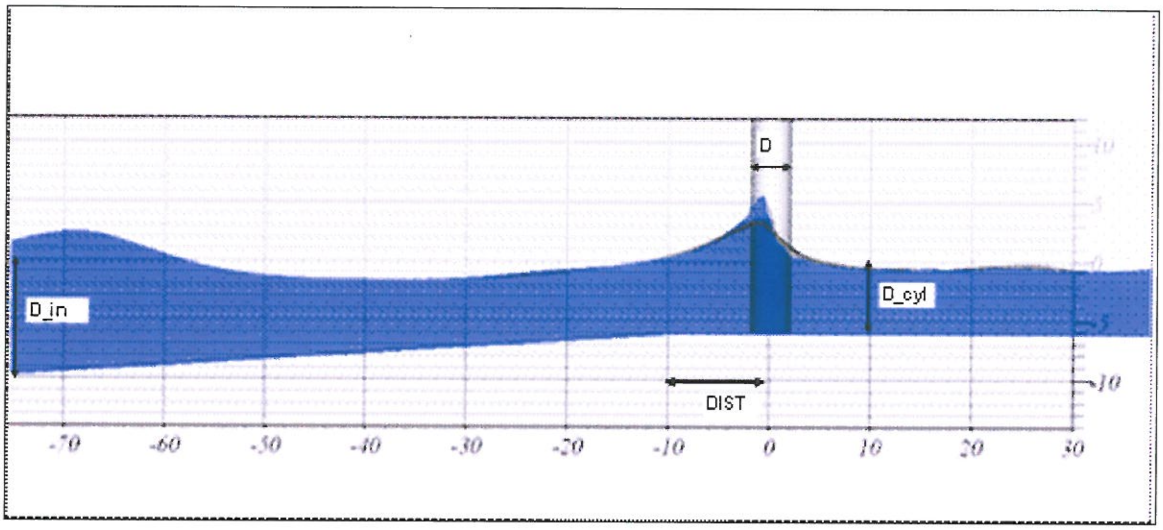


Figure 5. Definition of numerical parameters.

Simu-lation	D_cyl	H_cyl	T	Dia	KC	H_cyl/ D_cyl	L_cyl	D_in	Ks	H_in_ bound	Slope	Dist
1	6	4	8	**4**	**4.47**	0.67	57.5	10	0.9392	**3.757**	1:20	10
2	6	4	8	**2**	**8.93**	0.67	57.5	10	0.9392	**3.757**	1:20	10
3	12	5.496	9	**4**	**4.47**	0.458	87.9	16	0.9794	**5.383**	1:20	10
4	12	5.496	9	**2**	**8.93**	0.458	87.9	16	0.9794	**5.383**	1:20	10
5	6	4	8	**4**	**4.47**	0.67	57.5	10	0.9392	**3.757**	1:20	15
6	6	4	8	**2**	**8.93**	0.67	57.5	10	0.9392	**3.757**	1:20	15
7	6	4	8	**4**	**4.47**	0.67	57.5	10	0.9392	**3.757**	1:20	25
8	6	4	8	**2**	**8.93**	0.67	57.5	10	0.9392	**3.757**	1:20	25
9	6	4	8	**4**	**4.47**	0.67	57.5	10	0.9392	**3.757**	1:20	50
10	6	4	8	**2**	**8.93**	0.67	57.5	10	0.9392	**3.757**	1:20	50

Table 6. Numerical test parameters.

The KC number is found from the near-bed orbital velocities, determined by stream function theory, assuming regular waves and constant water depth equaling the water depth at the pile (D_cyl), wave height equaling the wave height at the pile (H_cyl) and wave period T.

Numerical results

Figure 6 shows a snapshot of the near-bed velocities for simulation 1 and 2. The figures clearly show that separation does not form for the large diameter pile $(KC = 4.5)$, while it develops for the small diameter $(KC = 9)$; this is in accordance with flume observations, see for example Sumer and Fredsøe (2002). The sediment transport for non-cohesive sediment depends on the so-called shields parameter, which expresses the ratio between the bed shear stress (driving forces) and the gravity (stabilizing forces)

$$\theta = \frac{\tau}{g d_{50} \rho (s-1)}$$

Where τ is the bed shear stress, g is the gravity, d_{50} is the grain diameter, s is the relative density of the bed material, ρ is the water density. The shear stresses are often replaced by the friction velocity, defined as $\tau = \rho U_f^2$.

In order to study the influence of wave breaking, the bed friction velocities have been compared for simulation 2, where the wave is just about to break, but has not broken yet, and simulation 8, where the breaking process is at a mature stage.
A quadratic relation between the bed shear stresses and the near-bed velocities: $\tau = 0.5 \rho f U_{bed}^2$ has been assumed, a constant friction factor f. The friction velocity can be determined from the near-bed velocity $U_f = \sqrt{0.5 f} U_{bed}$.

Figure 8 shows the friction velocities, assuming a friction factor equal $f = 0.01$.

By comparing the friction velocities in the two cases, it is evident that wave breaking only has a small influence on bed shear stresses; there is even a tendency that the bed shear stresses are lower in case of wave breaking. This supports the experimental finding that scour is only weakly dependent on wave breaking.

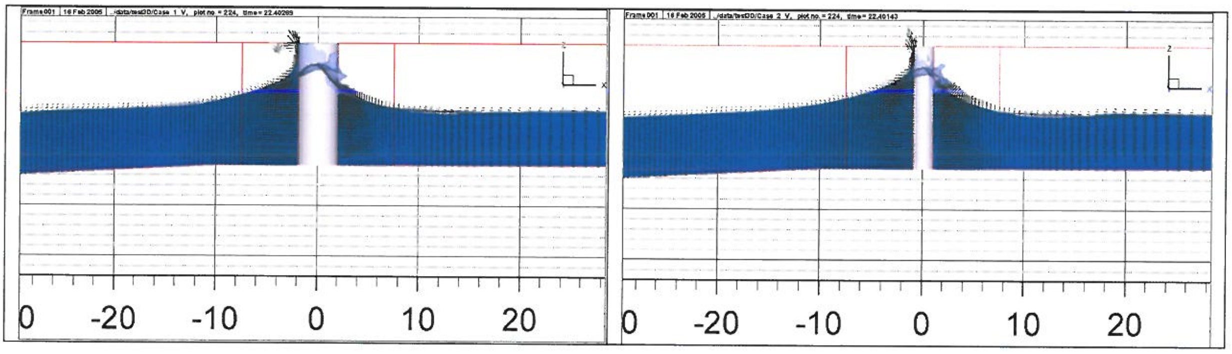


Figure 6. The wave hitting the cylinder at the same phase for simulation 1 (left) and simulation 2 (right).

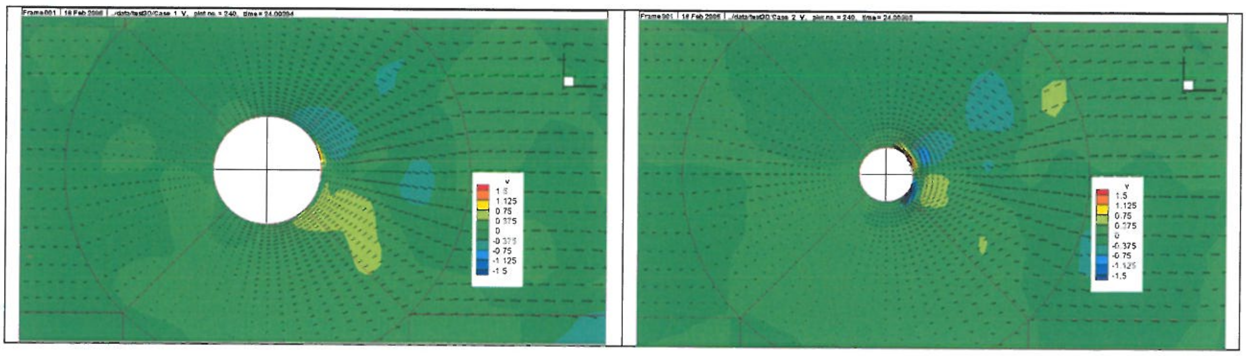


Figure 7. Snapshot of the bed velocities (m/s) for simulation 1 and 2, the colors indicate the flow velocity in the y direction (perpendicular to wave propagation

direction).

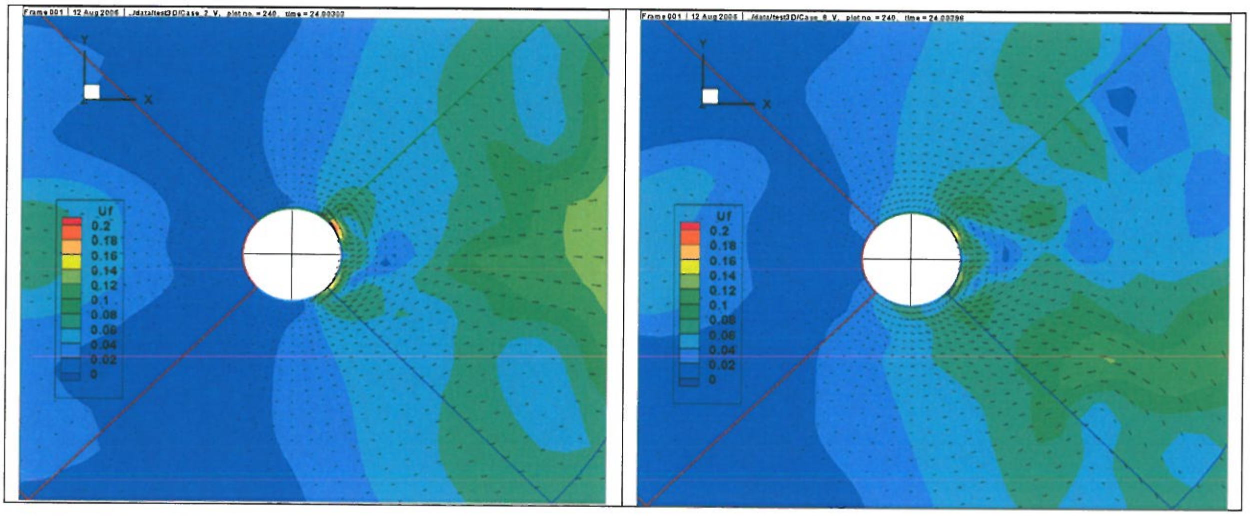


Figure 8. The friction velocity at the same phase for simulation 2 (left) and simulation 8 (right).

For the same near-bed flow properties, physical scour experiments have been performed at Aalborg University, also with and without breaking waves. The physical experiments study focuses on the time development of the scour processes as well on the final scour hole.

Results

The physical experiments as well as the numerical study show that the effect of breaking waves only has a small influence on the scour hole development.

Discussion

Normally the presence of waves will not increase, but might even decrease, the scour depths compared with situations where only currents are present.
In literature many equations for estimation of scour depths can be found. Jensen (2004) lists a comprehensive overview of existing formulas.
Sumer (2002) reanalyzed a lot of data from literature, and came up with the very simple equation for the maximum scour depth S, S = 1.3 D. Most data related to non-breaking situations.
Bijker and Bruyn (1988) wrote: *The depth of this scour is in the order of 1.5 times the pile diameter. In case of breaking waves this value can be, however, considerably higher. This paper gives a large influence on the scour prediction in breaking waves.*
In the present study, no such dependency was seen. Looking closer at the figures in the Bijker and Bruyn paper, it seems that it is not the presence of the piles that causes the erosion, rather it is the normal bed development. Similar to a shore line which changes with the magnitude of the incoming waves.

Conclusion

Good agreement between physical tests and numerical calculations was shown. The numerical model seems to be able to pick up the correct physics.
Only minor influence from the breaking waves was seen on scour depths. Scour depths in breaking waves and in non-breaking waves were comparable.

Acknowledgement

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